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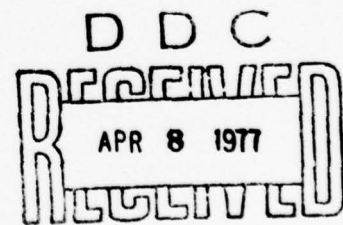
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POSITRON ANNIHILATION: FROM QED TO NDT A PRIMER AND
A REPORT ON THE FOURTH INTERNATIONAL CONFERENCE ON
POSITRON ANNIHILATION

DR. A. SOSIN

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
The use of positron annihilation as a tool is showing a remarkable growth in a number of areas: chemistry, materials, science, biology, etc. The Fourth International Conference on Positron Annihilation, held at Helsingor, Denmark on 23-26 August 1976 brought together investigators from each of these areas, as well as those in positron physics itself. This report summarizes the presentations at the meeting and attempts to emphasize the highlights of the developments in the field of positron annihilation. As a preliminary to the conference review, this report also provides an introductory survey of positron

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physics and experimental methods for readers largely unfamiliar with positron annihilation.

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POSITRON ANNIHILATION: FROM QED TO NDT A PRIMER AND A REPORT ON THE
FOURTH INTERNATIONAL CONFERENCE ON POSITRON ANNIHILATION
HELSINGOR, DENMARK 23-26 AUGUST 1976

I. Introduction

A conference on positron annihilation may conjure up an image of
a narrow topical meeting. In fact, the Fourth International Conference
on Positron Annihilation (Helsingor, Denmark; 23-26 August 1976; 160 papers;
21 nations) was quite remarkable for its breadth. Its coverage proceeded
from considerations and tests of quantum electrodynamics (QED) to techniques
directed to application in non-destructive testing (NDT). The vitality
of the field was demonstrated by a breadth which includes dynamics and
mechanisms in chemistry, studies of defects and phase transformations
in materials science and solid state physics, biological inquiry, and
non-invasive applications for medical diagnosis. R.M. Lambrecht (I1)
reported at the Conference that the field of positron annihilation is
currently growing at the rate of 18% per year.

In a recent issue of *European Scientific Notes* (ESN 30-10:473), this
reviewer described some of the highlights of the Conference and his impres-
sions and predictions. The purpose here is to report on the conference
in greater detail since the proceedings have wide applicability, and,
as a preliminary, provide a somewhat elementary description of the phe-
nomenon of positron annihilation (PA), its instrumentation, methodology,
and applications. There exists a number of more complete descriptions
of PA. It is not the intention here to compete with these, to pretend
completeness or even uniform coverage; rather it is the hope that a rel-
atively short discourse will be of assistance to those who would like
to acquire sufficient background to appreciate PA and its potentialities.

II. Positron Physics & Methodology

Positron physics is not a new field; its history already occupies
a noble place in physics. The prediction of the existence of the positron
as an antiparticle to the electron followed from Dirac's relativistic
formulation of quantum mechanics in 1930. The verification of his pre-
diction came only two years later when C. Andersen, in his study of cosmic
x-rays, observed the tracks of positrons. Andersen's discovery was crowned
with a Nobel prize.

As an antiparticle, the only physical difference between an electron
and a positron lies in the sense of their charges, the positron being
positively charged and the electron negatively charged (which suggests
that renaming the electron as a negatron might be reasonable). There
is, however, an important difference between positrons and electrons in
our physical universe; namely, electrons swarm about in huge numbers while

positrons are rare. In fact, our universe is a hostile environment for positrons. The encounter between a positron and an electron is fatal (for both particles) and this ensures that the population of positrons remains close to nil. The few that do exist and their fleeting lives are the very essence of PA.

In most contemporary studies, positrons are obtained from the natural radioactive decay of the sodium-22 (^{22}Na) isotope. To conserve momentum and energy in this decay, the nucleus must emit still a third particle-- a 1.28 MeV photon (gamma). Both photon and positron are emitted simultaneously (within 10 psec); this permits the experimenter to measure the lifetime of the positrons since the detection of the photon serves as a zero time-marker. Since the positron lifetime is long compared to the time of transit of the photon from its parent nucleus to the detector, photon travel time corrections are unnecessary. The positron emerges from the ^{22}Na nucleus with 0.48-MeV kinetic energy, sufficient to penetrate a small amount of solid material. As a consequence, an alternate timing method has been developed by Coleman et al [J. of Phys. E 5, 376 (1972)] in which the ^{22}Na source is covered by a scintillator and the light emitted in this scintillator during the passage of a positron is efficiently collected in a photomultiplier and recorded. This alternative technique allows for greater efficiency in obtaining timed positrons; the standard technique is inefficient in sensing 1.29-MeV gammas, by comparison.

The positron lifetime is determined by the density of electrons along its path and the probability of an annihilation-encounter with an electron. Both of these considerations become of paramount interest to investigators, particularly to those who use PA as a tool. Inevitably, the positron does meet its suicide partner, but only, in the general case, after being slowed down in non-fatal collisions from its initially high to slow velocity. (The term slow velocity here signifies that the positron retains a kinetic energy of only a few eV.) To a good approximation, therefore, the positron is essentially at rest when PA occurs. If the positron and electron were in fact at rest at the critical moment, the resultant rest-mass energy could be dissipated in the emission of two photons, each with an energy of 0.511 MeV and directed in opposite directions. As stated, the positron is nearly at rest; but the electron, governed by Fermi statistics and bound by its large population in the case of solids, is, on the average, imbued with an appreciable kinetic energy of the order of a few eV. Therefore, the two photons do not emerge with exactly 0.511-MeV energy and are directed along lines which are off from 180° by milliradians. As a result of these considerations, there are three techniques to monitor PA. The first is the measurement of positron lifetimes, not a unique number but a distribution centered on an average value; the second is angular correlation (AC), the observation of the mismatch between the angular directions of the two positrons. A third, Doppler broadening (DB), centers on the energy of the gammas emitted in PA. These gammas are not monoenergetic, as might be inferred from this discussion; instead,

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there is a spread in energy due to the fact that gamma emission occurs from a moving source (i.e., the motion of the positron and electron in an annihilation act). Thus, the combination of an electron, with kinetic energy of 10 eV, and a positron, essentially at rest, will give a DB of about 1.5 keV to photons with about 511-keV energy.

While the two-photon emission mode satisfies energy and momentum considerations, it is not the only mode observed. More rarely, one finds three photons emitted. For investigators interested in positron physics, this is an important point. The fate of an electron and a positron on encounter is strongly affected by their spins (each $1/2$ $\hbar$) and, in particular, the sign of their spins. If the spins are anti-parallel, the net spin is zero. A two-photon emission conserves spin, since each photon carries with it a spin of $1\hbar$; obviously, the two photons would emerge with oppositely directed spins, giving a total spin of zero. Three photon emission must arise from annihilations in which the total spin of the electron-positron pair is $1\hbar$; i.e., when the electron and positron spins are parallel.

It is evident from this discussion that the details of encounters between positrons and electrons are central to PA. The typical history of a positron follows the following scenario. The positron is emitted from the decaying nucleus and travels, initially, with a near-relativistic speed, through some of the source material (sodium, say), through a backing material, perhaps, and on into the main target which might be gas, liquid or solid, depending on the experiment. In any case, the positron suffers encounters with a series of electrons; encounters with atomic nuclei may be disregarded here. Positron energy moderation overwhelmingly dominates the scenario initially; that is to say, encounters between positrons and electrons result in electron excitations within host atoms or in atomic ionization. On the average, a positron loses about $1/2$ of its kinetic energy on each encounter with an electron. Using this factor of $1/2$, the number of collisions, n, for moderation of a positron to a few eV-- say 5 eV--may be estimated by 5 eV $\cong E_O (1/2)^n \cong [5 \times 10^5$ eV] $\cdot (1/2)^n$, so that n~15 is a typical number of moderating collisions. The density of electrons in a condensed material is about 10^{24} cm^{-3} to 10^{25} cm^{-3}. Taking the former, a positron should encounter an electron about every Angstrom (10^{-8}cm). The distance between atoms in condensed solids is typically about 3×10^{-8}cm, perhaps a preferred estimate to use here. Using 3×10^{-8}cm, the total moderation path (not a straight line!) is, approximately

$$L = nl \sim 5 \times 10^{-7} cm$$

If the positron traveled with the velocity of light (approximately true originally but not after some moderation), the moderation time would be

$$t_m \sim \frac{L}{C} = \frac{5 \times 10^{-7} \text{ cm}}{3 \times 10^{10} \text{ cm sec}^{-1}} \sim 2 \times 10^{-17} sec = 2 \times 10^{-5} psec.$$

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The use of C is incorrect; 10^{-2}C would be a better estimate. Finally,

$t_m \sim 10^{-5}$psec,

negligible compared to any times encountered in PA experiments.

The slowing down to thermal energies ($\underline{1}$ eV at room temperature)
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requires the availability of eenergy states for electrons scattered by
positrons. The details of the (Fermi) statistics for electrons play
a role here. Many energy states are filled, in condensed materials.
The above calculation is no longer a valid approach; if extended, the
calculation would predict only a slightly longer time for full moderatation.
In fact, full moderation requires about 3 psec in metals. Energy state
considerations are even more severe in insulators, where occupation of
energy states is very important; the full moderation time may be 300 psec.
Thus we see already that the lifetime of a position is markedly affected
by the material environment.

PA events are overwhelmingly less likely until the positron energy
has been reduced at least to the few eV range. Even then, the fate of
the positron is somewhat uncertain. Instead of simple PA on positron-
electron encounter, a positron-electron pseudo-atom positronium (Ps) may
be formed.

Ps is a fascinating subject. Conceptually, Ps is simpler than hydrogen,
which usually is cited for its fundamental simplicity since it consists
of an electron and a proton (plus zero to two neutrons, in various isotopes).
In the vernacular of the nuclear physicist, Ps contains no baryons; its
particles are the lightest non-photonic particles known. The simplicity
is clear--and deceiving. It is the greater mass of the proton (1836 times
as massive as the electron) which permits the use of ordinary quantum
mechanics or, if necessary, the Dirac formulation. This permission is
denied in Ps, and the full use of quantum electrodynamics (QED) in the
application of a relativistic two-body equation is required. In addition,
the magnetic moment of a particle depends inversely on its mass so that
the magnetic moment of a positron is larger than the moment of a proton;
accordingly, the distinction between fine atomic structure and hyper-fine
structure vanishes since the so-called spin-spin interaction which determines
hyperfine structure is now comparable with the spin-orbit interaction.
The importance of these considerations to fundamental physics is readily
appreciated.

A Ps atom does not exist forever. If the positron and electron forming
Ps have spins oppositely directed, the lifetime of this "para-Ps" atom,
in its singlet's ^{1}S ground state, is 123 psec; the lifetime of "ortho-Ps,"
with total spin of $1\hbar$, is 140 nsec in its triplet ^{3}S ground state. Para-
Ps dies with the emission of two photons; three-photon emission occurs

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from ortho-Ps. The longer lifetime of ortho-Ps permits the observation of collision processes which, for example, convert ortho-Ps to para-Ps, since the formation of a para-Ps atom is almost inevitably followed by PA. This is one example of "positronium quenching."* (The existence of ortho- and para- atoms is well known in atomic physics; ortho-helium and para-helium are familiar examples.)

The probability that Ps is formed in a material is dependent on the nature of that material. The energetics of the formation have been generally described in the past by reference to the "Ore gap." To understand this "gap" (I think region would be a better term), it is necessary to note that the binding energy of Ps is a 6.8 eV. This result can be appreciated readily if one recalls that the binding energy of a hydrogen atom (in the ground state) is 13.6 eV. This is the case for one electron and a very heavy nucleus. For Ps, there are two particles with electronic masses, and the usual Bohr treatment of such an atom, taking into account the need to work in a center-of-mass coordinate scheme, introduces a factor of one-half.

If an atom or molecule is ionized and an electron is removed to become the partner of a positron in Ps, an energy equal to the ionization energy, E_i, of that atom or molecule is required; but, the 6.8-eV binding energy is retrieved. Therefore, the minimum energy to form Ps--the "threshold energy," is E_i-6.8 eV. For example, E_i = 24.4 eV for He; the threshold energy for Ps formation in He is 17.6 eV. If, on the other hand, the positron energy is greater than the lowest excitation energy, E_e, for that atom or molecule, excitations will compete with Ps formation. Accordingly, Ps formation is most probable in the (Ore) range between E_e and E_i-6.8 eV. In non-metals, E_e is generally greater than E_i-6.8 eV and a small "gap" exists for Ps formation. In metals, the reverse is true and one anticipates an absence of Ps formation.

Clearly the first experimental consideration is the positron source. Although a number of nuclei have been used or proposed (e.g., ^{103}Ru, ^{64}Cu, ^{58}Ca), ^{22}Na is still the great favorite. Frequently the Na is contained in aqueous solution of NaCl, activated in a nuclear reactor. The ^{22}Na is, for example, deposited as a very thin layer on a corrosion-resistant material--teflon, mica, and gold are in common use--to minimize absorption of positrons in this layer. Activities of several μCi are usual. The effects of PA in the source layer is generally subtracted by resorting to a time-resolution function to represent the apparatus. One can attempt to calibrate the function by using a ^{60}Co source in the same geometry, since ^{60}Co emits two simultaneous gamma rays of essentially the same energy.

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*Another example is "pick-off," in which the annihilation of ortho-Ps proceeds on collision of the Ps atom with a foreign electron, allowing for the apparent violation of conservation of spin since only two photons are emitted in pick-off.

A typical PA system for the measurement of positron lifetimes is shown in Fig. 1, taken from the article by R.M. West [*Advances in Physics* 22, 272 (1973); courtesy of Taylor & Francis Ltd.]. The gamma particle emitted at the birth of the positron provides a zero-time signal, and the time delay between its detection and the subsequent detection of a 0.51-MeV annihilation photon from the positron annihilation is measured by a fast-slow coincidence technique, employing time-to-pulse-height conversions and multichannel analysis. The timing discriminators in the fast channels are used to process the "raw" pulses from each detector in such a way as to define accurately the time of occurence of each detected event. The time-to-pulse-height converter produces a spectrum of pulses in which the amplitude of each pulse is proportional to the time interval between the detection of a pair of events in the detectors. These pulses are transferred to the multichannel analyzer for sorting and storage by a linear gate driven by coincident events in the slow energy in the slow energy discrimination channels, thereby providing identification of relevant pairs of events.
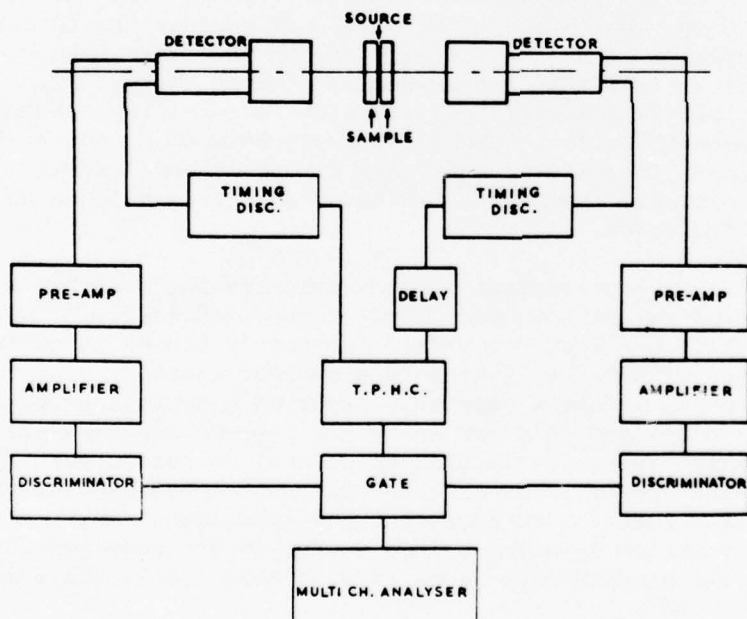
A typical setup for AC is shown in Fig. 2. The annihilation photons are detected by scintillation counters shielded from direct view of the source by lead collimators. Additional detector collimators define the instrumental angular resolution. The coincidence counting rate from the two detectors is measured as a function of the displacement of the moving detector. In the "long-slit" geometry, one dimension of the detector slit is made much larger than the width of a typical angular distribution, thereby yielding only one component of momentum for consideration.
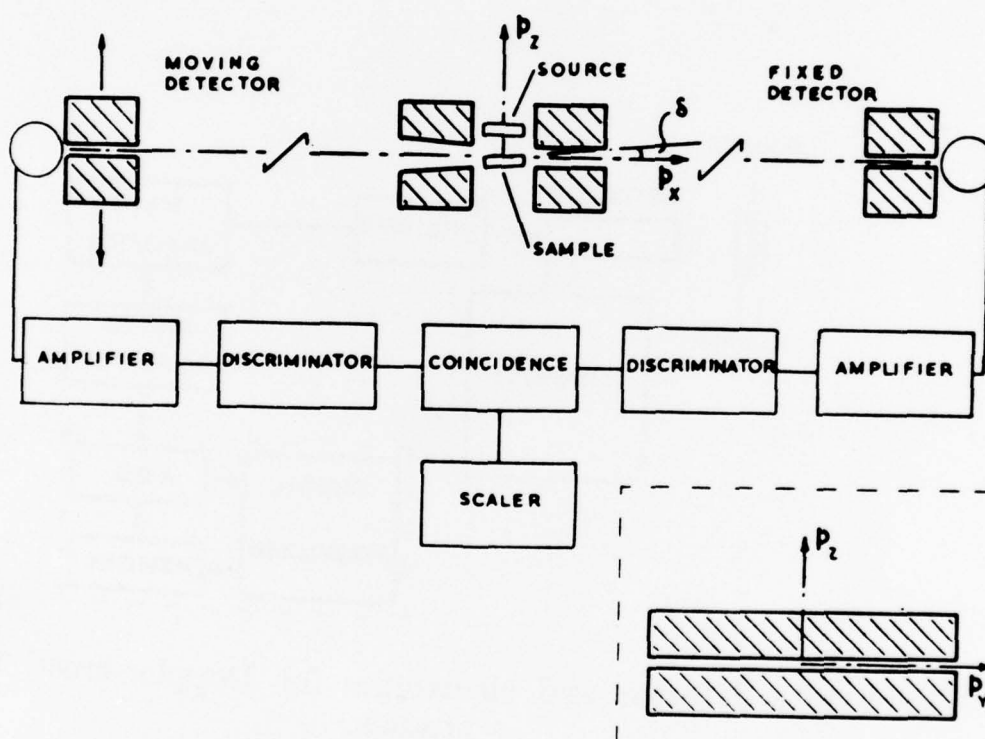
An angular correlation apparatus.   Inset : the long slit geometry.

For DB, see Fig. 3. Notice that the DB system has only one detector whereas the AC system has two. The obviation of the second detector and the incidence-counting mode makes the acquisition of data by DB much faster and provides for experimental configurations that might be difficult with AC. Solid state detectors [e.g., Ge(Li)] are used, requiring the refrigeration capacity of a cryostat.
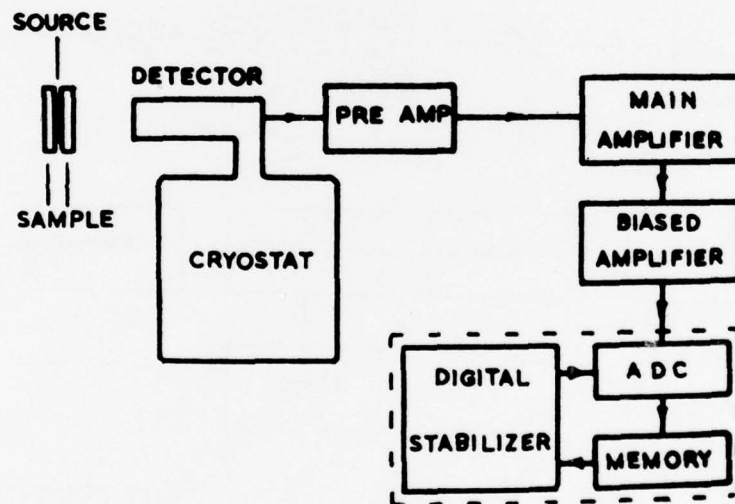
Ge(Li) solid-state detector and electronics for Doppler-broadening studies.

Some typical data for positron lifetimes in various materials are shown in Fig. 4. The lifetime of the positrons in the particular material are obtained from straight-line, longer-time portions of the curves, using the relationship

$$N = N_O [\exp(- t/\tau)].$$

However, a mere glance at the abscissae already indicate that the lifetime of positrons in In is the shortest of those displayed here, and in teflon, the longest. The peaked structure in each curve at smaller times is associated with instrumental and background occurrences which inevitably accompany any experimental system. In our examination of PA, we could ignore this peak structure. Unfortunately, accurate analysis requires a more careful subtraction of background using, typically, a Gaussian fitting technique for the peak.
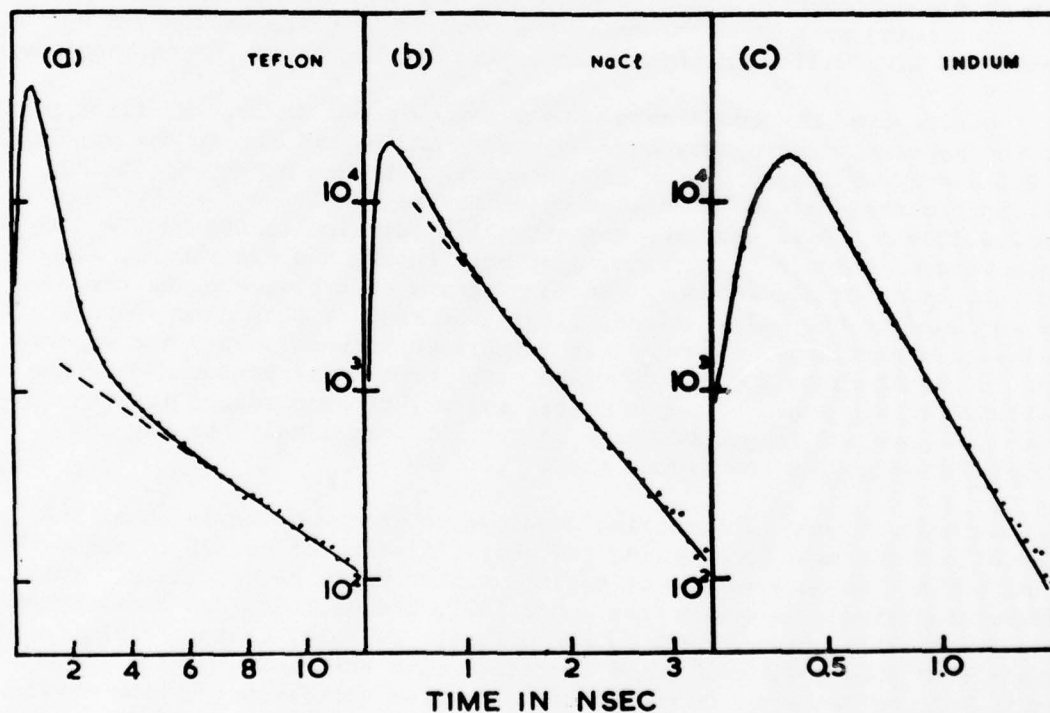
Typical lifetime spectra. (a) Molecular materials. (b) Ionic solids. (c) Metals. Note the variation in time scales for these figures.

For further details about systems and data displays and analysis, including the AC and DB cases, the reader should refer to journal literature.

III. Conference Report

The site of the Conference was the L.O. Skolen (Labor Organization School) in Helsingör. Which is an ideal location, with fine facilities for technical meetings. The school houses many conferences throughout the year and conferees are no doubt drawn by the excellence of the facilities as well as the beauty of the countryside. The arrangements and their execution left little to be desired.

It is almost inevitable in such meetings that the leaders in the field will occupy center stage. This was true here, too. One figure dominated the whole proceedings. Professor Stephan Berko has played the role of leader for a good number of years, and this Conference served to crown his many achievements. At the conference banquet, A.T. Stewart, himself a notable and long-time contributer to PA, presented a non-existent prize for outstanding work in PA to Berko and two of his collaborators, K.F. Canter and A.P. Mills, Jr. for their basic investigations in positronium.

Berko opened the conference with a review paper (R 1). He first pointed out the apparent discrepancy between theory and experiment in the prediction of the energy splitting of the ground state, a Zeeman effect splitting. The experimental values, in frequency units, are 203.3870 ±, 0.0016 GHz and 203.3849 ± 0.0012 GHz; the theoretical prediction is 203.4040 ± 0.0006 GHz. These values indicate the precision of both theory and experiment, along with the existing discrepancy. Berko suggests that higher order terms, not included in the calculations, lie at the root of this discrepancy. A similar discrepancy is present in comparison between theory and experiment on the PA rates for the ^3S state. The problem is compounded by the existence of two types of experimental values, those obtained from experiments in gases and in powders (see below). Interestingly, theory and experiment agree for the ground state ^1S.

Perhaps the most interesting development is the observation of the n=2 excited states. Considering the short lifetime of Ps, it is not surprising that the observation of excited states would be difficult. This observation eluded experimenters until 1972. The exciting new development is a drastically new approach to the effort. In 1974, Canter, Mills, and Berko found that positrons leave a surface with surprisingly high efficiency when a beam of "slow" positrons (a few electron volts) strikes the surface of a solid target. The efficiency depends on the target material, the positron energy, and the temperature. MgO powder was the earliest material used effectively (up to 80 or 90 % conversion efficiency); SiO_2 is also used.

With this new technique, two observations of particular note have been reported. Canter, Mills, and Berko measured the fine structure in the n = 2 levels--the Lamb shift--and found it to be in agreement with theory, when the theory includes radiative correction terms. On the other hand, there is a discrepancy in the experimentally measured PA rates for the ^{3}S decay which is reverse to expectation. Gas measurements give $0.7275 \pm 0.0015 \times 10^7$ sec^{-1} and $0.7262 \pm 0.0015 \times 10^7$ sec^{-1}; powder measurements give a shorter decay rate: $0.7104 \pm 0.0006 \times 10^7$ sec^{-1}. This difference remains one of the current puzzles.

One final word concerning positron physics before proceeding: The new activities in positron physics, made possible by advances in equipment and techniques, promise to spur much activity. However, it seems unlikely to me that such progress will have any notable impact on the use of PA as a tool for a very considerable time, if at all.

The contents of the Conference were divided into eight sections; this report will generally follow that organization. However, the reader should be cautioned that the divisions are very imperfect.

GASES

Studies of positrons in gases might be classified as standard--those in which positron behavior is examined under reasonably straightforward conditions--and unusual investigations, in which low temperatures and high gas densities are major factors. E.G. Griffith (R2) reviewed the former; K.F. Canter (R3) spoke about the latter in a review paper.

In the standard studies area, measurements of the total scattering cross section are most common. Significant advances in experimental procedures have stimulated the field recently. The first is the high emission of positrons from the bombardment of MgO by positrons from a ^{22}Na source. These emerging positrons are emitted with a reasonably well-defined energy range: 1.0 ± 0.5 eV. The measurements of total cross section are time-of-flight measurements, and the start-pulse in the timing sequence arises from the passage of the ^{22}Na positrons through thin plastic scintillators. The "beam" of positrons from the MgO source (actually a thin layer of MgO granules mounted on gold vanes), after acceleration to the desired energy, passes down a 1-m tube through the chosen gas. Those positrons which are unscattered are detected in a NaI detector at the end of the path. The positrons are constrained to a helical path down the tube by an axial magnetic field. This has the disadvantage that positrons which are scattered into the forward direction by gas atoms or molecules may still be carried on to the final detector, complicating interpretation. Very recently, Coleman and Griffith have gone to a smaller scattering chamber. At the center of the chamber is a 80 mm long scattering cell in which the chosen gas resides. The inevitable leakage of target gas from the chamber is accommodated by strong pumping in the scattering chamber.

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Using this apparatus, Griffith and Coleman and collaborators have measured cross sections up to 400 eV for all of the rare gases and for a variety of molecular gases. The agreement with the theoretical calculations of Humberston is excellent. The same measurements allow the determination of the annihilation rate for slow positrons in gases, and comparison with theory is made with a parameter, Z_{eff}, which is the effective electron density for PA in the scattering atom. $Z_{eff} = 3.94$ for He, where the atomic number is Z=4, in agreement with theoretical calculations of Campeanu and Humberston. Agreement is good with the other rare gases as well. The only discrepancies that may arise concern the non-linearity of the measured parameters at high gas pressures. In a contributed paper (A13), Coleman *et al* reported that Z_{eff} falls from a value of 30.6 to 24 with pressure in scattering from nitrogen. (Notice that Z_{eff} is reported as both greater and less than the static value of 2Z=28 for N_2.)

The impression that Griffith's review paper gave was that their standard gas experiments are currently in a stage of considerable refinement. A pattern of agreement with theory generally seems to be forthcoming. The more tantalizing apparent disagreements, which seem to spark research enthusiasm, are emerging more slowly, but inevitably.

In the contributed portion of this section, several papers (A1-3) dealt with increasingly sophisticated scattering calculations (e.g., polarized orbital approximation); these efforts are still not complete. On the experimental side, W.E. Kauppila *et al* (A4,5) reported the continuing exploitation of their experimental technique--the production of intense beams of monoenergetic positrons using a Van de Graaff accelerator.

With the intensity of positrons that they have achieved, Kauppila *et al* have been able to demonstrate clearly the existence in the noble gases of a Ramsauer-Townsend effect, that is, the minimum in the scattering cross section as a function of positron energy. The minimum occurs around 2 eV. The cross section increases sharply at the threshold energy for formation of Ps, and inflections in the cross section are evident, particularly in the heavier gases, at the threshold for the first excitation and for the ionization of the gas.

The review of the more unusual studies in gases by Canter (R3) were built on the observation that a free particle description of positron interactions with gases at high pressures and low temperatures no longer suffices. Manifestations of this discussed by Canter were positron-induced clusters and positron-induced cavities. In contrast with the standard gas work, where theories predict behavior in impressive detail and experiments tend to confirm theory, Canter's area is marked by a relative absence of theory, and experiments are less developed, as well.

It was reported over a decade ago that annihilation of slow positrons below 7 K appeared anomalous in that below a positron energy above thermal

it becomes very large. The model which appears to fit this observation,
qualitatively, is a local condensation of helium atoms--the electrostriction
of these atoms, induced by the presence of the positron with its positive
charge. Quantitatively, the light mass of the positron makes the calculation
of this clustering difficult and the abruptness of the behavior is far
from understood. To compound the problem, it has been reported more
recently that weak electric fields have a notable effect on the clustering,
contrary to expectation.

While positrons cause a condensation, Ps causes the reverse, a cavity
formation. Qualitatively, this is to be expected. Ps repels helium,
with its closed electron shells, by virtue of the Pauli Principle. But
the size of the cavity is surprising. Bubble radii range from 10 to 20 Å,
depending on density and pressure. This cavity formation occurs in liquid
helium, as well.

The above observations hold for ^{4}He. They also occur for ^{3}He, with
quantitative shifts. That might be surprising, too. The similarity,
nevertheless, in ^{4}He and ^{3}He could lead one to the conclusion that quan-
tum effects may be of minimal importance. Accordingly, one would anti-
cipate similar effects in other rare gases. This logic is confounded
by the observations that the slow positron life time spectra for neon
gas is unaffected by temperature (down to 34 K) and densities (up to 10^3 amagat;
1 amagat is one STP density or 2.7×10^{19} molecules cm^{-3}). At the same
time, Ps bubbles are formed in neon, but no bubbles have been observed
in argon up to 50 amagat!

In a contributed paper, Brisbon and McNutt (A10) presented data which
suggest positron-hydrogen compound formation. They find that the anni-
hilation rate for Ps in H_2 is "sensible" at 77 K, 250 K and 293 K; but
the annihilation rate for positrons is non-linear with density, indicating
that the annihilation mechanism requires the interaction of a positron
with more than one hydrogen molecule. P. Hautojarvi et al (A 11) presented
the experiments on positron lifetime in liquid ^{4}He and ^{3}He, summarized
by Canter, while J.B.Smith et al (A 12) reported work in solid helium
at 1.7 K and 4.2 K (under pressure of 140 atm). The magnitude of some
of these effects may be judged by Hautovarji's report that the lifetime
of ortho-Ps in liquid ^{4}He and ^{3}He decreases from 100 nsec to 50 nsec as
the pressure is increased to 60 atm. Clearly the study of PA in the
nearly-condensed systems is most exciting.

METALS

The work that was collected under this classification is dominated
by the determination of Fermi surfaces, a subfield of PA that is now
reasonably old in itself. Alternative methods for determining the Fermi
surface of a metal are limited to high purity metals. This limitation

does not apply for PA, so the use of PA here was greeted with great expectation. To date, the actual achievements have been minimal. Perhaps the greatest PA accomplishment was the demonstration, that the Fermi surface of pure metals are truly sharp. However, there has been sufficient improvement in experimental PA techniques and equipment that the expected returns may soon be forthcoming. Mijnarends (R4) reviewed Fermi surface work. He acknowledged that PA cannot compete with alternative Fermi surface techniques in precision, but the latitude in sample purity (including alloying), crystal perfection, and available temperature of study make PA an effective tool. Mijnarends stressed the need for close cooperation between theorists and experimentalists for proper design of experiments. Experimental work has included Cu, Ni, Zn, Cd, Mg, Pb, Co, Zr, Sb, Bi, and Th among the monatomic metals. V_3Si have been reported. Perhaps the most promising alloy work has been Cu alloyed with Ge, Si, Ga, Ni, and Zn; the Hume-Rothery phase rules come to mind immediately in such systems. But there is other work in progress, as well: Ni-Zn, Bi-Sb, and even the glassy metal system, $Pd_{0.775} Cu_{0.06} Si_{0.165}$. Some of these systems were discussed in other papers.

A.T. Stewart reported Fermi surface work almost 20 years ago. Now he is in the forefront of a development which may be revolutionary in its impact on Fermiology. R.J. Douglas and A.T. Stewart (B14) presented a paper which discussed the experimental precision available--approaching 0.1 %--and showed results for Mg, Zn, Cd and Ag-Zn. They emphasized the importance for the future of 2-D angular correlation experiments. In fact. J. Mader et al (B15) presented the first detailed 2-D AC measurements of 2-gamma annihilation from oriented single crystals of Al. Here, for the first time, it is possible to obtain details of the tail of the energy distribution, by moving away from the $p_z=0, p_y=0$ region of momentum space. According to the authors, Ümklapp processes predominately determine the nature of the tail distribution.

The theory of Fermiology was presented in several contributed papers; their impact requires close study. The experimental results of the group under M. Doyama (Univ. of Tokyo) are readily appreciated; S. Tanigawa et al (B3) represented measurements of AC and PA in fully annealed Ag, Mg, Zn, Cd, Al, In, Sn, Pb, Cu, and Ni. They seperated their AC observations into two components, one parabolic and the other Gaussian, and identified these with PA involving valence and core electrons. A plot of total annihilation rate vs electron density gives a set of points with no apparent pattern (Li, Na, Rb, and Cs data obtained by others were included). However, a plot of annihilation rate by valence electrons (or the corresponding area of the AC curve) gives two distinct straight lines. One is formed by the data from Al, Sn, Zn, In, Co, Cu, and Ag; the remaining elements define the second line. It is suggested that all the elements on the second line form hydrides, which is not the case for those on the first.

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ALLOYS

This classification may be viewed as a catch-all for several types of investigations, including shifts in the Fermi surface with alloying (due to varying electron/atom concentration); alloy phase changes; amorphous alloys; order-disorder alloys; and hydrogen-bearing systems. The work in this classification is in a more elementary stage than previous classifications, and the work of Doyama and collaborators is setting the pace. They have done a most effective job of "skimming the cream" and are busy lapping up the milk, too.

Doyama's group presented four papers in this section (as well as four in the section labeled defects in metals, below). In one (D7) they reported observations in amorphous alloys. The alloys were $Pd_{0.85}Si_{0.15}$ and $Ni_{0.81}P_{0.19}$. Little discernible difference was found in the samples following crystallization. This indicates that the alloys contain few vacancies, at least of the variety seen in more common metal systems. The same largely negative result also mitigates against the other common picture of a glass, a model of microcrystalline disorder, since the large number of pseudo-grain boundaries one would expect should also give rise to a very large positron lifetime, for example. And these are the two leading models of the glassy state.

Doyama himself (D8) presented results about phase transitions, using PA. His group has now looked at a large number of systems and classified the results into three types. I. ($AuCu_3$, Cu-40a/oPd) These exhibit first order phase transitions; the peak value at zero angle in AC, N(0), appropriately shows a continuous change at the phase transition temperature. II. (Beta CuZn, Cu-17a/oPd, Cu-22a/oPd). These exhibit second order transitions and a discontinuous change in N(0) at the transition temperature. III. (Cu-25 a/oPd, Cu-30 a/oPd, Cu-15 a/oMn). These are alloys which suffer order-disorder transitions with lattice transformation. Doyama and group have also looked at precipitation alloys. Most of these alloys display changes in N(0) in an active temperature range which Doyama and colleagues tend to ascribe to vacancy effects, but the matter is not settled. In study of the beta CuAl martensitic alloys also show signs of vacancy effects and, as reported in another paper (D9) covering the classical Martensitic alloy Au-47.5a/oCd, hysteresis and pretransformation indications are seen. In a fourth paper (D10), positron lifetime in Fe-29.5a/oNi was studied. The lifetime was resolved into two separate components each of which was monitored as a function of annealing temperature (from 20°C to 625°C) after martensitic transformation. One lifetime, τ_1, is sufficient to describe the observations until nearing the start of transformation. Then a second longer-lifetime component arises, increases rapidly at the transformation start-temperature, peaks in intensity at the finish-temperature to 40%, and finally decays in value to under 20% with increased temperature. Again, these effects are attributed to the defects which accompany the transformation.

The Japanese activity in this category was extended by three papers from Tohoku Univ. In the first (D3) the Fermi surface of Cu-Pd alloys

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was studied by AC. The <111> Fermi surface hump was found to decrease
approximately linearly with Pd concentration up to 20% Pd, in agreement
with a rigid band model. Above 20%, the radius of the hump remained constant,
which the authors explain as the detachment of the hexagonal face of the
Brillouin zone at around 25% Pd but a continuing hump even up to 60% Pd.
The <001> and <011> radii fit the rigid-band model well. Some evidence
for long-period order structure and contact of the Fermi surface with the
<110> superlattice Brillouin zone near 20% Pd was also presented. A second
paper (D4) discussed the intricacies of Fermiology in the Cu-Ge and Ag-Al
systems. The third paper (D12) concerned PA in VD_x and VH_x, with
$x = 0.02$ to 0.67. At low H or D concentrations, the alpha phase exists;
H or D are randomly arranged in tetrahedral interstitial sites. At high
concentrations, the beta phase exists; H or D occupy octahedral sites in
an ordered array. The AC observation is that the $N(0)$ value is enhanced
at the smallest D concentration studied; little else is altered even at
51% D, where the phase transition occurs. The authors conclude that posi-
trons are trapped in vacant interstices in nearest or second nearest inter-
stitial sites to D atoms.

In still another application, G. Brauer *et al* (D15) applied PA lifetime
techniques to V_3Si, a prototype "A-15" (β-W) superconducting material.
A theoretical relation, they use the observed lifetime to deduce a unit
sphere radius for electrons of 1.85 a.u.. Unfortunately, no band calculations
are as yet available for comparison.

DEFECTS IN METALS

This was the most active section of the Conference, as judged by
the number of papers. M.J. Stott (R5) first talked about the quantum
mechanical treatments of positron potential energy in crystals, emphasizing
that all treatments point to a tendency of positrons to concentrate in
spaces between ions, even in metals, even if the metals are perfect. How
much easier it is for a positron to find a resting place if an ion is
removed in metal! The resulting configuration is, of course, a vacancy;
thus the great activity in the use of PA to study vacancies and vacancy
aggregates follows upon this logic. According to Stott, positron trapping
at vacancies is reasonably well understood although the temperature depen-
dence of distribution of the trapped positron and the positron modification
of the vacancy deserve further study. Extensions of the single vacancy
concept are obvious to divacancies; the dilatational region near an edge
dislocation suggests that dislocations should also be effective traps for
positrons. Voids are certainly attractive as positron traps. Yet, Stott
pointed out that the jogs on a dislocation may be more important than the
dislocations themselves; that the step on a void surface might be most
important for voids.

Stott noted that, in disordered substitutional alloys, irregular
arrangements lead to positron localization and that positrons will prefer-
entially shift toward ions with lower valence.

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The task of reviewing the increasing volume of studies on defects in metals fell to R.M.J. Cotterill (R6). About one-half of the review talk of I.K. MacKenzie (R7) on the temperature dependence of PA in metals was concerned with trapping by vacancies; the remaining half concerned self-trapping, a separate section of this Conference in itself (see below).

MacKenzie traced the development of studies on positron trapping by vacancies, starting with observations of C.G. White in a Master's thesis at Dalhousie University in 1961. The crucial observation was that the positron lifetime varied rapidly with temperature in a temperature region just below melting in Zn. Since then, trapping by vacancies--which are present in relatively great number in this temperature range--has been observed in a number of metals. Equally fascinating is the fact that such trapping has not been observed in several metals--Hg, Ga, Na, Bi, Sn, Te, Tl. MacKenzie listed three reasons which may cause this failure: the potential well created for the positron by the vacancy may be too shallow to retain the positron; the annihilation characteristics of a positron at a vacancy trap may be very similar to the free state; and the vacancy concentration, even near the melt, may be too small. He emphasized the importance of the third reason, particularly. He showed a plot of the heat of fusion vs. the melting temperature for a series of metals. The plotted points fell on two straight lines (according to Richard's Rule, the entropy of fusion, a constant, should be the ratio of the heat of fusion to the absolute temperature) with Sn and, possibly, Hg being somewhat ambiguous in position. One of the lines includes those metals which do not display positron-trapping near the melt. MacKenzie further indicated that these metals show anomalously slow self-diffusion, again pointing to low vacancy concentration, and have high ratios of the coefficient of self-diffusion to melting temperature.

In the last review paper of this section, K. Petersen (R8) discussed recent development in the investigation of voids and the growth of voids, by use of PA. The study of voids dates back to their initial observation by Cawthorne and Fulton at the Dounreay Reactor in the UK in 1966. Voids can vary in size from only a few vacancies to hundreds of Å in diameter. Superlattices of voids, and even dislocated superlattices, have been observed. The first PA measurements on voids were made by a Danish group; they found that the width of the AC curve was 6.1 mrad in Mo, compared to 12.4 mrad found in nominally perfect Mo. Subsequent lifetime measurements in Mo gave a value of more than 500 psec; this is four times greater than in void-free Mo. Subsequently, work has been reported in several metal systems, irradiating with neutrons, alphas, or electrons, at both high and low temperatures, and in the presence or absence of helium gas (which apparently acts to stabilize voids). PA in plastically deformed metals may also be attributed in part to voids, as well. Petersen emphasized the importance of correlating PA observations with other measurements, such as electrical resistivity during annealing, internal friction, transmission electron microscopy, and small-angle x-ray scattering.

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There were 41 contributed papers in this section, which demonstrated many of the points of the review papers. On the theoretical side, R.M. Nieminen and C.H. Hodges (E1) discussed the theory of positron surface states. Ordinary surface trapping is important in itself; in addition, trapping at the surfaces of vacancy aggregates and voids is a matter of immediate concern. Tam (E2) treated the problem of a single vacancy, emphasizing the electron-positron-defect three-way interaction; T. McMullen (E3) stressed the effects of phonons; M.A. Shulman and Berko (E31) used a modified Wigner-Seitz model.

With respect to single vacancies, Doyama (E3) gave evidence that formation energies can be correlated with "critical temperatures" which arise in lifetime and AC plots. Fluss *et al* (E4) presented simultaneous positron lifetime and DB measurement results in Al in which the importance of temperature was apparent. On using a simple trapping model--one in which a positron either is free or is bound at a vacancy--they found a formation enthalpy of vacancies of (0.52 ± 0.02) eV from DB and (0.75 ± 0.02) eV from lifetime measurements, a major disagreement. In arriving at these values, they assumed that positron characteristics do not depend on temperature. Better agreement, but not full agreement resulted when some temperature-dependence was included. Given sufficient data, it is not necessary to make assumptions about temperature-dependences, as demonstrated by S.C. Sharma and S. Berko (E32). Instead, one may deduce the temperature-dependence if he is confident of the trapping model. Sharma and Berko reported a detailed study in Pb in which they allowed the data to be unconstrained fully in their fitting procedure. They found that the lifetime of positrons in the bulk may not be the quantity which arises directly from the analysis; rather, it may be a mix of the two lifetimes deduced (in addition to a source lifetime term). The moral of these papers is that, while PA is very sensitive to the presence of vacancies, interpretation is not straightforward and curve-fitting is fraught with dangers.

The role of temperature dependence for trapping of positrons at a variety of defects was central to studies of B.T.A. McKee and A.T. Stewart (E33). Some of their results are that trapping at vacancies in quenched gold is temperature-independent; trapping at dislocations is weakly temperature-dependent in deformed Cu, measured from 10 K to 300 K; trapping at grain boundaries is weakly temperature-dependent in Zn-22 at % Al and depends on grain size; trapping at voids has a small temperature-dependence below 100 K and a larger and positive one between 100 and 300 K. It is clear that the whole matter of temperature dependence currently is largely unsettled.

Vacancy studies are familiarly performed as a function of temperature. J.E. Dickman *et al* (E7) have added the important parameter of pressure. They deduce a vacancy formation volume of 6.1 ± 0.2 cm^3/mole for In, using $N(0)$ from measurements of AC; we can anticipate many more pressure experiments.

S.W. Tam and R.W. Siegel (E8) considered a tantalizing question. If one assumes that a positron is trapped near a vacancy, what happens

when the vacancy migrates? Tam and Siegel have analyzed the elements of
the problem--the recapture of a detrapped positron, the force exerted by
the positron on atoms surrounding the vacancy. They conclude that PA
characteristics are essentially unmodified in most metals. In the alkali
metals, however, vacancy migration can lead to positron detrapping, but
thermal detrapping is the more important process in these metals. They
also conclude that the lattice relaxations around a vacancy are significantly
affected by a positron trapped at that vacancy.

In alloys, vacancy concentrations are generally enhanced by the binding
of vacancies near solute atoms. The use of PA, via AC, was reported by
W. Triftshauser and R. Jank (E5) to deduce binding energies: 0.12 ± 0.03 eV
for Mg in Al and 0.23 ± 0.10 eV for Ge in Cu. The formation of Guinier-
Preston zones and precipitation are closely related topics, and R. Nagai
et al(E27) showed that PA, through a "line-shape parameter", can be a monitor
of these processes in Al(Cu); P. Schultz *et al* made a similar study in
the brass (Cu-Zn) system.

Despite any concern about our inadequate understanding of positron
trapping at single vacancies, there is a great acceleration of work on
trapping at voids. Considering the technological implications of voids,
this movement is readily explained. There is a purely scientific ration-
alization, also. Voids have been mainly observed by electron microscopy,
but the size resolution is limited in the microscope. One hopes that PA
will help span the size range from single vacancies up to void sizes that
allow microscopy.

V.W. Lindberg and J.D. McGervey (E15) studied neutron-irradiated
(5×10^{21} neutrons cm^{-2}) Al and resolved their spectrum into three lifetimes.
The longest (550 psec) remained constant during post-irradiation annealing.
A second trapping lifetime showed an increase from 250 psec to 400 psec
during annealing in the range where voids disappeared (above 315°C). D.
Segers *et al* (E16) also looked at neutron-irradiated Al and measured positron
lifetimes as a funtion of fluence. They fitted their results to a two-
lifetime fit. The longer lifetime (presumably the one best described by
defect-induced traps) increased in intensity from 31% to 41% and in value
from 281 to 320 psec as the fluence varied from 1.21×10^{19} to 8.76×10^{19}.

P. Hautojarvi *et al* (E17) analyzed the data of Eldrup *et al* on the
annealing of irradiated Mo and deduced the variation of lifetime as a
function of the number of vacancies in the void. According to this cal-
culation, the lifetime increases from about 200 psec for monovacancies
to a saturation value of about 460 psec, reached near 15 vacancies; the
bulk lifetime in Mo is about 140 psec. N. Thrane *et al* (E18) confirmed
that the lifetime in their neutron-irradiated Mo is not notably changed
beyond 20 vacancies, although impurities (e.g., A) can cause a further
increase in void-trapped positron lifetime (E19). Helium bubbles, in
alpha-bombarded Mo, give results qualitatively similar to voids (E20).

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The interaction of positrons with dislocations underlies the work of several papers (E23, E24, E25, E26). This interaction offers the attractive possibility of using PA as a tool for studying fatigue and, possibly, becoming a non-destructive testing (NDT) tool. Byrne *et al* (E12) fatigue-cycled cold-rolled copper and observed a *decrease in positron* lifetime at 7×10^4 cycles. This is correlated with a decrease in x-ray particle size. The lifetime saturation due, apparently to dislocations, was about 170 psec. A more complicated pattern was reported by H.E. Hjelmroth (E37) in fatigued Al. They found two lifetimes--215 psec and 260 psec-- which they attributed to trapping at dislocation jogs and to vacancy defects, respectively. G. Dlubek and O. Brummer followed the recrystallization of cold-rolled Cu by PA, using AC, and deduced an activation energy of 24 ± 1 kcal/mole.

If so much work is possible in metals, what about semiconductors? Using AC, M. Bernardin *et al* (E28) measured PA, using AC, as a function of temperature in GaSb and InSb and found no temperaturedependence. Again, the results may be interpreted as evidence for insufficient vacancy traps or insufficient difference in characteristics of such traps. Doping of Si and Ge produced an apparently negative effect as well. However, it is reported (E29) that deformation in Ge does change the AC observations. Furthermore, S. Dannefaer *et al* neutron-irradiated Si and arrived at lifetimes of 325 psec and 435 psec for divacancies and quadrivacancies, respectively. Clearly, work in semiconductors in an elementary stage.

INORGANIC SOLIDS.

This is the title given in the program; non-metals would probably have been more appropriate. The investigations in these materials parallel those in metals to a large extent, but the amount of activity is less. This probably is because of the substantial number of diagnostic tools available for these materials and not for metals.

A. Dupasquier (R9) described the complex situation in ionic crystals, as compared to metals, with regard to the states of positrons. He discussed closed-shell states, in which a positron is coupled to a multi-electron system where the total spin of the system is zero, and quasi-Ps states, in which a positron is coupled to a multi-electron system which has one electron with an unpaired spin. The additional complexities thus introduced make the interpretation of PA in ionic crystals very difficult. To add to this burden, there is a host of distinguishable defect centers, each apparently with its own characteristic to influence PA. It is not surprizing that the several papers dealing with PA in ionic crystals discussed possible interpretations which markedly differ from each other.

Oxides, not generally considered ionic crystals, also fall into this section. Here a different consideration arises. We recall that the lifetime

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of ortho-Ps is 140 nsec. Ps formation in metals is apparently proscribed by the great abundance of electrons. But Ps does form in MgO and SiO_2 powders. Gidley *et al* (F8) reported on a series of measurements of the decay of ortho-Ps in fine-grained SiO_2 powders, where Ps is formed with surprising efficiency ($\sim$ 20-30%). A plot of the observed decay rate vs. density of the powder extrapolates to a value almost the same as free-space ortho-Ps. Significantly, the value of the decay constant in SiO_2 is 2% less than in free-space ortho-Ps. The formation of Ps might be accounted for by noting that the core electrons are available to positrons for annihilation and that the valence electrons are covalently coupled and, therefore, also unavailable. If this explanation is correct, one would anticipate that Ps formation in Si should be expected, but this is not observed. However, the negative observation in Si may arise from still another annihilation mechanism. The slower decay rate could indicate the existence of a real discrepancy between the calculated rate and theory. A preferred explanation would probably center around the physical effects present in the powder. However, Ford *et al* [*Phys. Rev. Lett.* 36 1269 (1976)] considered this possibility, including effects of surface bound states, collisional interactions with the powder grains, and Stark shifts, and concluded that none of these could account for the lifetime-shift. S.J. Tao and S.Y. Chuang (F9) proposed a new explanation in which the shift is attributed to the incomplete thermalization of Ps in these powders. Consequently, a Doppler shift is introduced, leading to the observed effect.

P.U. Arifov *et al* (F10) studied $NiO-Al_2O_3$ powders. These were progressively heat-treated to promote sintering and, thereby, reduce porosity, in order to study the effect of surface states on PA. If surface states stabilize Ps, one would expect a reduced component of lifetime with sintering. Only above 600°C was this observed. Below this temperature Arifov *et al* saw the reverse, which they then ascribed to pick-off annihilation due to some type of grain structure stabilization.

In still other systems in this section, P. Hautojarvi *et al* (F11) studied Li_2O-SiO_2 glasses; G. Brauer and G. Boden examined silica glass. Hautojarvi *et al* reported that the morphology and activation energy of bulk crystallization are dependent on the degree of phase-separation. These deductions follow from the use of annihilation lifeshape measurements, testifying to the richness of information that is available in PA, with suitable experimentation and analysis. The approach of Brauer and Boden is similar and, according to them, points to the occurrence of a "preordered state" in their silica glass.

SELF TRAPPING

The increase of lifetime of positrons which occurs in metals at high temperatures is due, as discussed above, to the increased number of vacancies. Another ramification of trapping by vacancies occurs in the line shape of AC plots. Very similar line-shape characteristics occur in some metals

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at temperatures well below those where the vacancy effect can be observed. The consensus is that positrons are trapped here by themselves, in effect; they dig their own hole through a dilatational distortion of the lattice in their own vicinity. This effect was first observed by MacKenzie (R7) and is firmly established now, particularly in the case of Cd but also in In and Zn. Self-trapping is apparently absent in Ga, Hg, and Bi.

From a simple experimental point-of-view, positron trapping may be seen as an anomaly in the temperature-dependence of PA. This has been the emphasis of A. Seeger and colleagues in Stuttgart, and a paper by Teichler *et al* (C1) reanalyzes self-trapping using an atomistic model, not in the continuum approximation of previous treatments. Since self-trapping involves local atomic relaxations, the diffusion of positrons poses an additional complication that was considered. A simple Arrhenius-type temperature dependence no longer applies. A somewhat different position is held by Tam (C2), who uses a percolation theory approach to calculate the probability of a positron being trapped by the thermal fluctuations themselves. He finds that this is unlikely. Instead he and S.K Sinha (C3) propose that there is a phonon-induced separation of the positrons and electron charge clouds which leads to the increase in the positron lifetime. Further experimental observations were reported by several papers (4-8).

CHEMISTRY.

This is another burgeoning area of PA. As a classification at the Conference, chemistry included mostly organic systems, polymeric materials, and liquids. It is a very heterogeneous classification, with the concern for Ps formation a reasonably common denominator. The invited paper (R10) was less a review of the area of chemistry than a presentation of a new model for Ps formation. The earliest model for Ps formation, a hot-Ps model, was built on the radiation chemists' experience with hot electron models for radiation effects in organics. This was followed by the Ore model, described earlier in this report. Mogensen distinguishes his spur model as a dynamic model in which Ps formation reactions compete with ion-electron recombination, electron and positron reactions with solvent molecules, and a host of other possible reactions. The Ore model concentrates on a single event to a much greater extent.

Ore defines a positron spur as a cluster of reactive species, such as the positron, ion-electron pairs, and radicals formed when the positron loses the last part of its kinetic energy in a material. To this reviewer, the positron spur bears a great deal of similarity to the displacement spike familiar to investigators in irradiation effects in non-organic materials, compounded by additional electronic processes possible in organics. Most of the evidence cited by Mogensen for his model originates in organic liquids. The center of this observation lies on the intensity of a long lifetime component observed more frequently there. The intensity varies with system, reaching 55% in tetramethylsilane.

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Tests of the different models, as well as the more general understanding of PA in organic systems, concentrate heavily on observing the rate of Ps formation in different systems and with various additives. A number of papers described such observations.

Two of the most stimulating papers under the heading of chemistry could well be the forerunner of a new classification of biology. Y-C Jean and H.J. Ache (G13) measured the formation constants for a series of molecular complexes of vitamin K_1 and tocopherol with amine and other donors. They chose a series of molecular complexes of tetracyanoethylene and nitrobenzene with donors such as hexamethylbenzene and mesitylene in bezene solution as model substances. E.D. Handel *et al* (G14) investigated the relationship between positron lifetime and protein structures and reported the effect of temperature, pH, concentration and ligand ligand binding on PA parameters in two model proteins. Both investigations are of a pioneering nature and presage the birth of still another area of investigation to which PA will be applied.

APPENDIX I

OS = Oral Session   Ps = Positronium
PS = Poster Session   P = Positron(s)

List of Review and Contributed Papers

Review Papers

R1 Berko, S., "Tests of Q.E.D. On The n = 1 and n = 2 States of Ps". OS

R2 Griffith, T.C.,"Scattering of Low Energy P in Gases". OS

R3 Canter, K.F.,"Localized States of P and Ps in Gases". OS

R4 Mijnarends, P.E.,"Progress in Positron Fermi Surfaces and Momentum
              Density Work". OS

R5 Stott, M.J.,"Spatial Distribution of P in Metals and Alloys". OS

R6 Cotterill, R.M.J.,"Crystal Defects Studies Using P Annihilation on
              on appraisal of the current situation".

R7 MacKenzie, I.K.,"Temperature Dependence of P Annihilation in Metals". OS

R8 Petersen, K.,"Studies of Voids with P". OS

R9 Dupasquier, A.,"P in Ionic Crystals". OS

R10 Mogensen, O.E.,"The Spur Model of Ps Formation". OS

R11 Shantarovich, V.P.,"Ps Quenching and Inhibition and their Correlation".
              OS

A. GASES

A1 McEachran, R.P. et al.,"P Scattering from Noble Gases". PS

A2 Jean, Y.-C. et al,"Polarization Potential: Failure of First-Order
              Methods for P-Hydrogen and P-Helium Elastic
              Scattering". OS

A3 Ferrante, G. et al,"P-Alkali Atom Low-Energy Elastic Scattering by
              A JWKB Approximated Polarized Orbital Method". PS

A4 Stein, T.S. et al,"Measurements of Total Cross Sections for Low
              Energy P Scattering from Inert-Gas Atoms: Experi-
              mental Techniques". PS

C-38-76

A5 Kauppila, W.E., et al,"Measurements of Total cross sections for low-energy
                        P Scattering from Inert Gas Atoms: Experimental
                        Results". OS

A6 Grover, P.S.,"Calculation of Positron Velocity Distributions in Argon
                  and the Possibility of Observing Ramsauer Minima in
                  P - Atom Scattering". PS

A7 Paul, Derek,"On the Total Cross Sections of Ps in Molecular Gas Collisions".
                  PS

A8 Campeanu, R.I., et al,"Diffusion of P in Helium Gas". PS

A9 Arifov, P.U., et al,"P Spectra, Drifting in He, Ne, Ar". PS
                                for
A10 Brisbon, R.D., et al,"Evidence/ P Compound Formation in Hydrogen Gas". PS

A11 Hautojarvi, P., et al,"P Lifetimes in Liquid Helium-4 Helium-3". OS

A12 Smith, J.B.,Jr., et al, "Orthops Decay in Gaseous, Liquid and Solid
                        Helium". OS

A13 Coleman, P.G., et al,"Slow P in Nitrogen Gas". PS

A14 Srivastava, M.P.,"P Annihilation in Noble Gases in the Presence of
                      High Frequency Electric Field". PS

A15 Muheim, J.T.,"On A General Relationship Between the P Life Time
                  and the Intensity Structure of the Spark Mass Plasma from
                  Dielectric Solids". PS

A16 Brenton, A.G., et al,"An Investigation of P Collisions with Helium Gas
                        Atoms Using Low-Energy P Beams". PS

A17 Bninski, A.H., et al,"Monte-Carlo Method for Correcting for Forward
                        Scattering in a P scattering Experiment". PS

B. METALS

B1 Stachowiak, H., et al,"Exact Treatment of Kahana's Equation for a P
                        in an Electron Gas". OS

B2 Kögel, G.,"P Pseudopotentials and Pseudowave Functions". PS

B3 Tanigawa, S., et al,"P Lifetimes in Real Metals". PS

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B4   Wakoh, S., et al,"Angular Distribution of P Annihilation Radiation
                in Aluminum-Theory". PS

B5   Shiotani, N., et al,"Angular Distribution of P Annihilation Radiation
                in Aluminum-Experiment". PS

B6   Kontrym-Sznajd, G.,"P Annihilation in White Tin". PS

B7   Sekizawa, H., et al,"Angular Distribution in Cr and Mo". PS

B8   Kanhere, D.G., et al,"Anisotropies in the Angular Correlation of Ni
                and Cu". OS

B9   Nakao, Y.,"P Annihilation Rate in Transition Metals". PS

B10   Goodbody, G.S., et al,"A P study of the Conduction Electrons in
                Chronium". PS

B11   Mijnarends, P.E.,"Two-Dimensional Angular Correlations in Ferro-
                Magnetic Iron".   PS
B12 *

B13   Tsuchiya, Y., et al,"P Annihilation Study in Ultrafine Particles of
                Noble Metals". PS

B14   Douglas, R.J., et al,"Accurate Fermi Surface Diameters". OS

B15   Mader, J., et al,"Electronic Momentum Densitites by Two-Dimensional
                Angular Correlation of Annihilation Radiation in
                Aluminum". PS

C.   SELF-TRAPPING

C1   Teichler, H., et al,"On the Theory of Self-Trapped P in Metals". OS

C2   Tam, S.W.,"Can Lattice Thermal Fluctuations Trap P?". PS

C3   Tam, S.W.,"Theory of the Temperature-Dependence of Bulk P Lifetimes
                in Metals". PS

C4   Smedskjaer, L.C., et al,"On the Temperature Dependence of P Annihi-
                lation in Cadmium". OS

C5   Kim, S.M. et al,"Evidence for Self-Trapped P in Cadmium Below the
                Vacancy Trapping Region". OS

C6   Stoll, H., et al,"P Annihilation in Metals in Thermal Equilibrium
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* B12 Mukherjee, S.C., et al, "P Annihilation in Ferromagnetic Cobalt", PS

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C7   Singh, K.P., et al,"P Trapping in Cadmium". PS

C8   Segers, D., et al,"on the Evidence of P Self-Trapping in Indium." PS

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D1   Mijnarends, P.E, et al,"Electron Momentum Density in Random Alloys". PS

D2   Harthoorn, R.,"P Annihilation Angular Correlation Experiments on Ag,
               Pd, and AGPD-Alloys". PS

D3   Hasegawa, M., et al,"The Fermi Surface of Cu-Pd Alloys Studied by
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D4   Suzuki, To., et al,"The Fermi Surfaces of the HCP Cu-Ge and Ag-Al
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D5   Swiatkowski, W., et al,"P Annihilation in Bimetallic Systems". PS

D6   Koenig, C., "On the P Annihilation in Metallic Alloys". PS

D7   Tanigawa, S., et al,"P Annihilation in Amorphous Alloys". OS

D8   Doyama, M., "Studies of Phase Transitions by Means of P Annihi-
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D9   Tanigawa, S., et al,"P Annihilation in Martensitically Transformed
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D10 Troev, T.,"Angular Distribution of Annihilation Gamma-Quanta in Zinc
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D11 Rozenfeld, B., et al,"Investigation of P Annihilation in Ni-H System".
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D12 Hasegawa, M., et al,"P Annihilation in the V-D (H) Alloys". PS

D13 Meurtin, M., et al,"P Annihilation in Ordered Fe-Al Alloys". PS

D14 Troev, T.D., et al,"P Lifetime in Iron-Nickel Alloy". PS

D15 Brauer, G., et al,"P Lifetimes in V_3Si". PS

D16 Dezsi, I., et al,"P Annihilation and Mossbauer Studies on $Cu_x Zn_{1-x}$
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E2 Tam, S.W., "Two-Component Density Functional Theory and P-Vacancy
            Interaction in Metals". PS

E3 Doyama, M., "The Formation Energies of A Vacancy in Pure Metals and
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E4 Fluss, M.J., et al, "Simultaneous P Lifetime and Momentum Measurements
                of the Vacancy Formation Enthalpy in Aluminum". PS

E5 Trifthäuser, W., et al, "Vacancy Binding Energies in Alloys by P Annihi-
                    lation Experiments". PS

E6 Schultz, P., et al, "The Influence of Composition on Vacancy Formation
                Enthalpy in the Brass (Cu-Zn) System". PS

E7 Dickman, J.E., et al, "Vacancy Formation Volume in Indium from P Annihi-
                    lation measurements:

E8 Tam, S.W.,et al, "On the Effect of Vacancy Migration upon Trapped P Annihi-
                lation in Metals". OS

E9 Petersen, K., "Stage II Migration of Point Defects in Molybdenum". PS

E10 Gauster, W.B., "P Annihilation Defect Signatures in Irradiated Metals". OS

E11 Wallace, J.P., et al, "P Probing of Engineering Alloy Substructures and
                    Microstructures". PS

E12 Byrne, J.G, et al, "P Studies of Fatigue, Hydrogen Embrittlement and
                    Radiation Damage in Metals". PS

E13 Hinode, K., et al, "P Trapping Mechanisms by Lattice Defects". PS

E14 Evans, J.H., et al, "A P Annihilation Investigation into the Annealing of
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E15 Lindberg, V.W., "P Lifetimes in Voids and other Defects in Neutron-Ir-
                    radiation Aluminum".

E16 Segers, D., "P Annihilation Study of Neutron Irradiation Induced Voids
                in Aluminum". PS

E17 Hautojarvi, P., et al, "Dependence of P Annihilation Parameters on the
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E18 Thrane, N., et al, "The Relationship Between Void Size and P Lifetime in
                  Neutron Irradiated Molybdenum". PS

E19 Thrane, N., et al, "The Effect of Impurities on the Lifetime of P in
                  Voids in Molybdenum". PS

E20 Mogensen, O., et al, "The Use of Positron Annihilation to Investigate
                  Helium Bubble Formation in Molybdenum Injected with
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E21 Hinode, K., et al, "A Study of the Annealing Behavior of High Temperature
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E22 Mantl, S., et al, "The Temperature Dependence of P Trapping by Different
                  Types of Defects". OS

E23 Hautojärvi, P., et al, "On Interactions of Dislocations and Impurities in
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E24 Nielsen, B., et al, "Aluminum Plastically Deformed at Liquid Nitrogen
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E25 Lichtenberger, P.C., et al, "Annealing of Plastically Deformed Nickel PS
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E26 Myllyla, R., et al, "A Study of Defects in Copper After Thermal Treatment." PS

E27 Nagai, R., et al, "P Study on the Aging of Al-Cu, Al-Cu-Sn and Al-Ag
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E28 Bernardin, M., et al, "Searching for P Tapping by Point Defects in
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E29 Arifov, P.U., et al, "P Annihilation in Deformed Germanium". PS

E30 McMullen, "The Effect of P-Phonon Scattering on P Trapping at Defects
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E31 Shulman, M.A., et al, "Angular Correlation of Annihilation Radiation from
                  Vacancy-Trapped VS Bloch-Wave P in Al and Pb". PS

E32 Sharma, S.C., et al, "A High Resolution Lifetime Study of P Trapping by
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E33 McKee, B.T.A., et al, "P Trapping at Various Defects in Metals". PS

E34 Rice-Evans, P., et al, "A New P Trapping Effect at Low Temperatures". PS

E35 **Rice-Evans**, P., et al ,"P Trapping in Deformed Copper in the Temperature
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E36 Kheloufi, K., et al ,"Lattice Defect Analysis by Electron Microscopy and
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E37 Hjelmroth, H.E., et al ,"Suggestion for Interpretation of Inhomogeneous
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F2 Hyodo, T., et al ,"Some Temperature Effects of P Annihilation in Alkali
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F4 Surbeck, H., "Lifetime of P in Silver Bromide". PS

F5 Tsuda, N., et al, "Lifetime of P in Ionic Compounds", PS

F6 Tsuda, N., et al, "P Annihilation in CoO". OS

F7 Hsu, F.H., et al, "p Annihilation in Deformed CaO". PS

F8 Gidley, D.W., et al,"Progress Report on Precision Measurements of the
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F9 Tao, S.J., et al,"Mean Life of Low Energy Non-Thermalized O-Ps in
              Powders". PS

F10 Arifov, P.U., et al,"Dispersed Substance Surface State Influence on Ps
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F11   Hautojärvi, P., et al , "A P Study of the Li_2O-SiO_2 Glass System". PS

F12   Brauer, G., et al, "Crystallinity of Pure Silica Glass Studied by P
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F13   Brauer, G., et al , "Heat Treatment of Pure Silica Glass Studied by P.
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F14   Dave, G.W., et al , "P Annihilation in Ferro-Electric Materials". PS

F15   Dean, G.W., et al , "P Annihilation in the Alkali Halides". PS

F16   Nagaranan, T., et al , "P Annihilation in F'Centers". PS

F17   Ramasamy, P., et al , "P Angular Correlation in Halides of RX_2 Type". PS

F18   Ramasamy, P., et al, "P Angular Correlation Studies of Phase Transitions
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F19   Dekhtyar, I. Ya., et al, "Anomalous Passing of P Through Crystals". PS

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             One-P Atomic Systems". PS

 G2   Schrader, D.M., et al "Approximate Molecular Orbital Theory for
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 G3   Mogensen, O.E., "Theory of the Annihilation Probability of Ps many-
             Electron System". PS

 G4   Tao, S.J., "A Mathematical Model for Ps Formation in P Radiation
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 G5   Maddock, A.G., "The Chemistry of Ps: Inhibition and Reactivity of
       et al   Solutes". OS

 G6   Ito, Y., et al , "Effect of Ethyl Halides on the Formation Probability
             of 0-Ps in n-Hexane and Neopentane". PS

 G7   Wikander, G., "Inhibition of Ps Formation by Chlorine- and Fluorine-
             Substituted Molecules in some Different Nonpolar Solvents".
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G8   Lévay, B., et al, "Correlation Between the Inhibition of Ps Formation
                    by Scavenger Molecules, and Chemical Reaction Rate
                    of Electrons with these Molecules, in Nonpolar Liquids".
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G9   Wild, R. E., et al, "On Ps Formation in Binary Mixtures of Organic
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G10   Okada, S., et al, "Temperature Dependence of Deconvoluted Spectra of
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G11   Madia, W.J., et al, "On the Annihilation Lifetimes of P Bound in
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                    Biographical Systems by P Annihilation Techniques". PS

G14   Handel, E.D., et al, "P Annihilation in Proteins". PS

G15   Mogensen, O.E., et al, "P Bound States with Chloride, Bromide, and
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G16   Skytte Jensen, B.,   "Ps Pickoff Annihilation in Pure Liquids".

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                    Ethylene". PS

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G25 Walker, W.W., "P Annihilation Studies of the Solid-Phase Behavior of Mixtures of two Long-Chain n-Paraffins". PS

G26 Lévay, B., et al, "P Annihilation Studies on Mixed Complexes of Bis (Dimenthyl-Glyoximato) Cobalt(III) with Unidentate Ligands". PS

G27 Arifov, U.A., et al, "Influence of Vulcanized Cross-Linking Distribution on the Ps Formation in Elastomers". PS

G28 Percival, P., et al, "Liquid Phase Muonium Chemistry". OS

G29 Cade, P.E., et al, "Influence of Correlation Effects on P Annihilation Lifetimes of Atom/P Systems". PS

G30 Cade, P.E., et al "Theoretical Observations on the Stability of $[0^-;e^+]$ $[s^=;e^+]$, and $[S^=;e^+]$ Systems". PS

G31 Anisimov, O.A., et al, "The Ps Formation in Condensed Matter and Condensed Matter and Conditions of Recombination of Charges in the Spur". PS

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H. METHODS

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H2 Eldrup, M., et al, "Estimates of Uncertainties in Analysis of Metal P Lifetime Spectra". OS

H3 Newman, D., et al, "A New P g-Factor Experiment at the University of Michigan". OS

H4 Takhar, P.S., "Penetration of Electrons and P in Chemical Compounds and Alloys". PS

H5 Takhar, P.S., "Non-Destructive Testing of Materials by P". PS

H6 Myllylä, R., et al, "The Improvement of the P Lifetime Results
                        by Advances in Detection Electronics and Data
                        Computing". PS

H7 Lund, S., et al,   "On Lifetime System Optimizing and Experiments
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                        other fast Scintillators". PS

H8 Jackman, T.E., et al, "The Correlation of P Age with Momentum of the
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H9 Smedskjaer, L.C., et al, "Stabilization of P Annhilation Data using
                        a Computer". PS

H10 Fluss, M.J., et al, "A Computer Based Data Acquisition System for P
                        Annihilating Spectroscopy". PS

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H12 Kirkegaard, P., et al, "Parafit: A Program for Analysing P Annihi-
                        lation Angular Correlation Curves". PS

H13 Berko, S., et al,   "A New 64 Detector Two-dimensional Angular
                        Correlation Apparatus". PS

H14 Douglas, R.J., et al, "A Two-dimensional Angular Correlation Machine
                        for Queen's University". PS

H15 Lynn, K.G., et al, "A New Doppler Broadening P Annihilation Technique:
                        Core Contributions in Al and Be".   OS

H16 Dezsi, I., et al, "A New Source Preparation Technique for P Lifetime
                        Measurements in Liquids". PS

H17 Lambrecht, R.M., et al, "Production of a Titanium-44-Scandium-44
                        P Source". PS

I. BIBLIOGRAPHY

I1 Lambrecht, R.M., "Antimatter-Matter Interactions. I. P and Ps". PS

I2 Singru, R.M., et al, "P Annihilation Data Compilation and Presentation".
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